Turbulence and Internal Tides on the Continental Slope

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LONG-TERM GOALS

My interest is in oceanic processes that contribute to stirring and mixing in order to understand their impact on larger scales. This includes phenomena ranging from the meso- (10 km) to the microscale (1 cm), with an emphasis on their interactions, including internal waves, tides, potential-vorticity-carrying finestructure (vortical mode), turbulence and double diffusion.

OBJECTIVES

My recent focus has been on how meso- and finescale flow fields interact with complex topography such as seamounts, canyons, ridges and the continental slope. Mixing in the stratified ocean interior is too weak to close the meridional thermohaline circulation (Ledwell *et al*. 1998). I am exploring whether topographically-enhanced turbulent mixing might be sufficient to do so, and determining what mechanisms are responsible for its generation.

APPROACH

During May 1998, I collected data off the Virginia coast in collaboration with Drs. John Toole and Ray Schmitt and Kurt Polzin (WHOI). This observational program (TWIST – Turbulence and Waves over Irregular Sloping Topography) was designed to characterize the internal wave and turbulence climates above a continental slope with 2-3 km wavelength corrugations running down the slope. Interaction of the corrugations with subinertial alongslope flows associated with topographic Rossby waves was thought to be a likely mechanism for internal lee wave generation. I conducted surveys with expendable current profilers (XCPs) and expendable CTDs (XCTDs) to obtain 3-D snapshots of velocity (u, v), temperature T, salinity S and vertical displacement ξ along and across the corrugations. These measurements complement moored array profile time-series (Toole) and fine- and microstructure profiling with the High-Resolution Profiler (Polzin). Under my supervision, postdoctoral researcher Dr. Jonathan Nash (now an assistant professor at Oregon State University) analysed the data and interpreted it in terms of simplified internal wave models.

Microstructure profiling revealed eddy diffusivities in the stratified bottom boundary layer more than one hundred times open-ocean levels between the 1000- and 1200-m isobaths; *identical* values are found using the Gregg-Henyey finescale parameterization for internal-wave-generated turbulence (Gregg 1989). Our goal was to determine the mechanisms responsible for this enhanced mixing.

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14. ABSTRACT
My interest is in oceanic processes that contribute to stirring and mixing in order to understand their impact on larger scales. This includes phenomena ranging from the meso- (10 km) to the microscale (1 cm), with an emphasis on their interactions, including internal waves, tides, potential-vorticity-carrying finestructure (vortical mode), turbulence and double diffusion.

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WORK COMPLETED

Analysis of the data is complete. A manuscript has been submitted to *J. Phys. Oceanogr*. (J.D. Nash, E. Kunze, J.M. Toole and R.W. Schmitt "Internal Tide Reflection and Turbulent Mixing on the Continental Slope") and is presently under revision. We examined the finescale data in the expendable surveys and the three moored profile time-series, focussing on the latter half of the record when an along-isobath semidiurnal energy-flux was observed and the expendable surveys provided spatial coverage. A decomposition by vertical scale of the semidiurnal signal reveals the dominant physics. A 2-D ray-tracing model following Eriksen (1982) reproduces many features of the observations.

RESULTS

In contrast to expectations, we found no evidence for internal lee waves based on the absence of corrugation-scale finestructure in the water column. While the flow in most of the water column was in excess of 10 cm s^{-1}, the near-bottom flow was too weak to generate waves [$U < N\alpha/(k_x\sqrt{1+f^2/N^2\alpha^2}) \sim 15\ cm\ s^{-1}$, where α is the slope and k_x the wavelength of the corrugations]. We also found no evidence for internal tide generation at the shelf break, consistent with numerical simulations of the region (Legg 2003). Fluctuations during the last half of the sampling period are dominated by semidiurnal oscillations. Analysis indicates:

- The near-bottom mean flow is *around* not *over* the topographic corrugations consistent with it being too weak to generate lee waves;
- The vertically-integrated internal-wave energy-flux is northward parallel to the continental slope at O(1 kW m^{-1});
- Cross- exceeds along-isobath velocity variance;
- Shear is intensified in the bottom 300 m and is predominantly semidiurnal in the latter half of the sampling period when the expendable surveys took place;
- Near-bottom dissipation and shear is enhanced between the 1000- and 1200-sm (WKB stretched meters) isobaths offshore of supercritical (M_2) across-slope bathymetry (right panel of Fig. 1).

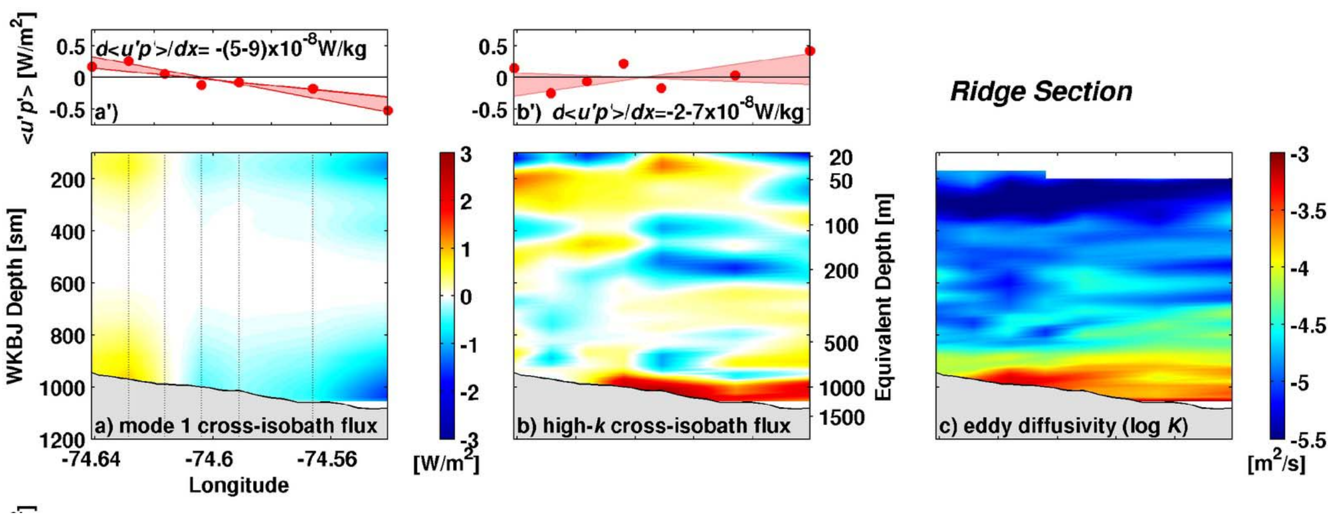

Figure 1: Across-slope sections along a corrugation ridge. Data are in a WKB-normalized format. Upper panels show vertically-integrated across-isobath energy-fluxes. There is convergence of low-mode onshore energy-flux (left) and divergence of high-wavenumber offshore flux which takes the form of an intense near-bottom beam emanating between the 1000- and 1200-sm (WKB stretched meters) isobaths (middle). Turbulent eddy diffusivities inferred from the Gregg-Henyey scaling (right) are enhanced only offshore of the near-critical, 1000-sm isobath and coincide with the high-wavenumber beam.

We hypothesize that enhanced semidiurnal shear and mixing is associated with reflection of a low-mode semidiurnal internal wave from near- and supercritical bathymetry. In support of this:

- While the net energy-flux is northward along isobaths, cross-isobath velocities exceed along-isobath velocities, and there is an abrupt cross-slope phase shift near the 1000-m isobath;

- Local generation of internal tides directly from barotropic semidiurnal motions is too weak to account for the observed shear or mixing (Legg 2003);

- A breakdown by vertical scale reveals that there is a cross-slope *con*vergence of mode-one energy-flux approximately balanced by cross-slope *di*vergence of high-wavenumber energy-flux plus turbulent dissipation (Fig. 1). Theory indicates that an *along-isobath* energy-flux is to be expected within one-quarter wavelength of the slope for the superposition of an incident incoming wave and reflected outgoing *across-isobath* wave;

- Beams of high-wavenumber flux radiate offshore from near the 1000-sm isobath. They coincide with high shear and turbulence signals (central panel of Fig. 1). Well-mixed bottom boundary layers more than 10-m thick are only observed offshore of supercritical topography.

To understand whether the observed semidiurnal shear could result from reflection of a low-mode internal wave off the continental slope, a simple ray-tracing simulation was performed. Bathymetry is assumed two-dimensional, ignoring alongslope corrugations. Boundary conditions consist of an onshore-propagating mode-one internal tide of 2 cm s^{-1} amplitude prescribed 150 km offshore.

Information travels along rays, obeying Eriksen (1982) reflection laws at the surface and bottom, until leaving the domain. The simulation reproduces most of the features of the observations (Fig. 2).

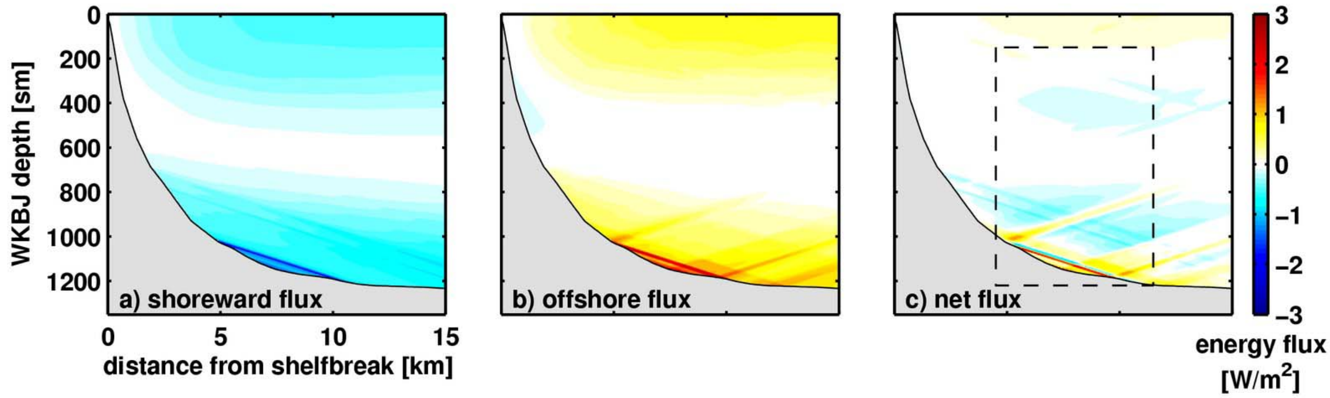

Figure 2: Energy-flux sections from a WKB ray-tracing model following Eriksen (1982). The left panel shows the shoreward flux, the central panel the offshore flux and the right panel the net flux. The box in the right panel denotes the area shown in Fig. 1. Note the near-bottom high-wavenumber variance between the 1000- and 1200-sm isobaths.

The ray-tracing simulations reproduce a 200-m thick layer of high-wavenumber variance on the slope between the 1000- and 1200-sm isobaths (Fig. 2), consistent with the observations (Fig. 1). The model predicts shears exceeding the stratification (Ri > 1). Parker MacCready (UW) is running numerical simulations with the Hallberg Isopycnal Model for comparison with the ray-tracing results.

IMPACT/APPLICATION

Our observations and model results suggest that the shear and mixing is associated with reflection of the low-mode internal tide with little dependence on the alongslope corrugations that originally drew our attention to the TWIST site. Elevated turbulence is also reported on the Oregon continental slope (Moum *et al*. 2002). Analysis of historical mooring data suggests that a similar critical reflection of a deep-ocean low-mode internal tide may be responsible. This suggests that continental slopes may be sinks for internal tides generated in the deep ocean. This contrasts with the earlier paradigm of internal tide generation at the shelf break (Prinsenberg *et al*. 1974; Baines 1982) radiating semidiurnal internal waves into the deep ocean and onto the shelf. In laboratory experiments of internal waves reflecting off sloping topography, McPhee-Shaw and Kunze (2002) found that the exchange of fluid between the turbulent boundary layer and the quiescent interior was controlled by the turbulent mixing at the boundary which could in turn be diagnosed by the convergence of across-slope internal wave energy-flux. This bears on both boundary-interior fluid exchange and intermediate nepheloid production.

TRANSITIONS

The energy-flux estimation technique is being used on other projects by the PI and others to examine internal tide energy budgets in Monterey Submarine Canyon (Kunze *et al*. 2002), across Mendocino Escarpment (Althaus *et al*. 2003), along the Hawaiian Ridge (HOME; Rudnick *et al*. 2003) and in the world ocean using historical current-meter records (Alford 2003).

RELATED PROJECTS

Larger fluxes are found radiating away from Mendocino Escarpment and the Hawaiian Ridge, as well as into the mouth of Monterey Submarine Canyon. Turbulence levels above the Virginia continental slope are comparable to those observed over seamounts, escarpments and ridges. Motivated by the Oregon slope microstructure measurements (Moum *et al*. 2002), Drs. E. Kunze, J. Nash and M. Alford have submitted a proposal to NSF to make finestructure measurements on the Oregon continental slope to determine if the same mechanism may be responsible. Existing evidence suggests that, except in abyssal waters below 4000-m depth, topographically-enhanced mixing, although 100-1000 times typical interior values (e.g., Kunze and Toole 1997), is not large enough to close the meridional thermohaline overturning cell as envisioned by Munk and Wunsch (1998). This would leave outcrop mixing as the only viable candidate for waters of 1-3 km depth in the temperate and tropical oceans (Sloyan and Rintoul 2001; Toggweiler and Samuels 1998).

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